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Mechanical Properties of Biomechanical Characteristics of the Mandibular Corpus Cross-section at the Molar Level

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Abstract The present study conducted structural analyses of hominoid mandibles by the finite element method (FEM) to clarify functional adaptations for mastication in primate lower jaws. Two-dimensional FEM model of the mandibular corpus cross section at the second molar was devised based on frontal CT images from the chimpanzee, gorilla, and humans. These models were loaded by external forces from different angles and the stress distributions were measured. Obtained stress distributions were also cross-specifically compared. The major findings are as follows: 1) in all three species, the principal components of stress become compressive in both the lingual and buccal sides and were equal in magnitude at a certain loading direction. The cross-section of each mandible body at the molar level is thus considered most resistant against bite force acting in this direction since bending stress is not generated under this condition; 2) this loading direction coincides with the tooth axis for all three subjects, but not with the principal axis of the cross-section. Stress distribution in the cross-section is mostly affected by the direction of bite force with respect to the tooth axis. Therefore, the mandibular corpus of hominoids was adapted to resist axial bite force. The present analysis did not find any significant difference among the species.

Key words Hominoids, Mandible, Biomechanics, Finite element method, Tooth axis

Introduction

The mandible is an important material for the study of human evolution owing to its abundant fossil records next to teeth. A widely acknowledged presumption is that teeth can be used to reconstruct dietary adaptation of fossil taxa. To discuss associations between mandibular morphologies and dietary adaptations, a functional morphological approach with a biomechanical premise is essential. Morphological studies on the mandible are numerous: allometry (Bouvier 1986; Demes *et al.* 1984, 1986; Ravosa 1990, 1991), cross-sectional properties (Daegling 1989, 1992; Daegling & Grine 1991). Daegling analyzed cross-sectional properties of the mandibular corpus of diverse primate taxa and revealed unique specialization in robust australopithecines (Daegling 1989) and intrageneric differentiation of diet and morphological features in the genus *Cebus* (Daegling 1992). Bioengineering studies such as the load test (Daegling & Hylander 1997), in vivo strain analysis (Hylander 1977, 1979, 1984, 1985; Daegling 1993) have also been conducted. Hylander conducted a series of studies where in vivo bone strains during mastication were measured and the results greatly developed knowledge of mechanical behavior of the mandible (Hylander 1977, 1979, 1984).

The recent technological development of computer science has enhanced mathematical simulations such as the finite element method (FEM) for bio-morphological studies. Mathematical simulation confers several benefits over experimental approaches. For example, simulation studies use various parameters, thus simulating cases more freely than in experiments on living subjects. In addition, internal stress and strain distributions of the whole object can be calculated.

Numerous FEM studies of the human mandible from the medical, dentistry, and engineering fields exist (Knoell 1977; Korioth *et al.* 1992; Tsutsumi *et al.* 1993). However, with a few exceptions, those on non-human primates are scant (Chen & Chen 1998). The present study conducts FEM analyses on the cross-section of the mandibular corpus at the molar level in hominoids to obtain information about general mechanical properties of this region in primates as well as to depict different functional adaptations, if any, between humans and great apes.

Materials and Methods

The FEM models used in this study are based on dry bones of the common chimpanzee, gorilla, and humans. The chimpanzee and gorilla specimens are from males and are housed at the Department of Anatomy, Dokkyo University School of Medicine. The human skull is also male and it is housed at the Department of Anthropology, The University of Tokyo. All were adults with the third molar fully erupted but the wear was slight.

CT images of the mandibles at the buccal groove of the second molar on the right side (frontal section) were obtained. Based on these images, two-dimensional FEM models were constructed (Fig. 1). The elements of the model were two dimensional triangular solids and trapezoid solids. The numbers of the nodes and elements are 183 and 318, respectively, in the chimpanzee model, 261 and 452, respectively, in the gorilla model, and 263 and 447, respectively, in the human model. Six kinds of material were determined in the model: i.e., cortical bone, cancellous bone, enamel, dentin, pulp, and periodontium. For each material, proper Young's modulus and Poisson's ratio were given based on Stanford *et al.* (1960) and JSME (1988) (Table 1). The models were constrained at the lower quarter nodes on the external surface (Fig. 2).

The models were loaded at the center of the occlusal surface. Load was given in changing orientations: every 10° from the externally oriented direction (0°) to internally oriented direction (180°) (Fig. 3). In all experiments, the loading was 500N. The ANSYS Release 4.4A was used for mathematical experiments (Cybernet Co.). Average of the principal stress difference and mean strain energy was calculated by species and loading regime since these values are significant factors of bone disruption. Principal stress difference is supposed to be positively correlated with a given magnitude of bending moment in case of bones (Endo 1984).

Angles of the principal axis of the cross-section and the tooth axis were measured in each subject and relationships with stress distributions were examined. Every angle value in this study follows a common system in which the external orientation is defined as 0° and values increase counterclockwise (Fig. 2).

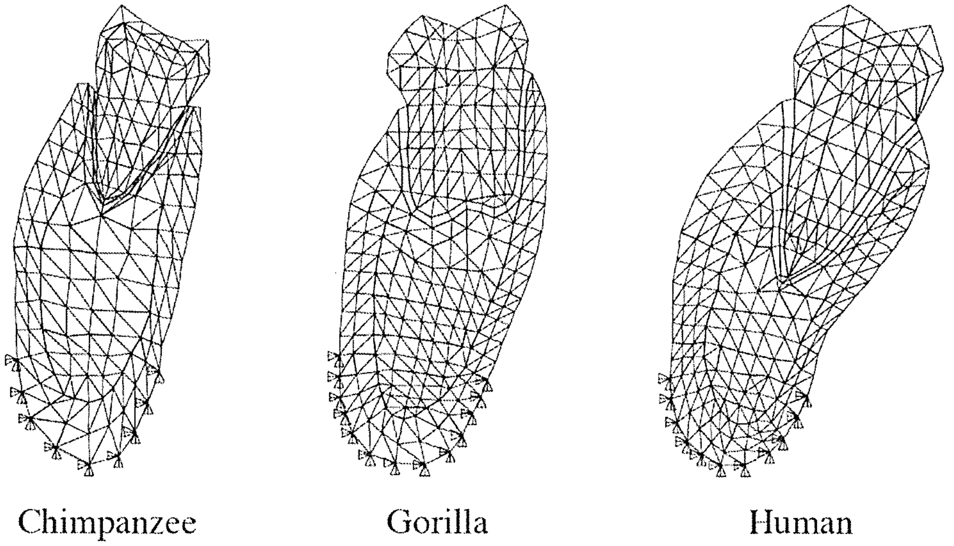

Fig. 1. FEM models of chimpanzee, gorilla and human (scaled to a same size). Models are based on frontal cross section of the right mandibular corpus at the buccal groove of the second molar (anterior view). Small triangles on the external surface of the corpus indicate the constrained nodes.

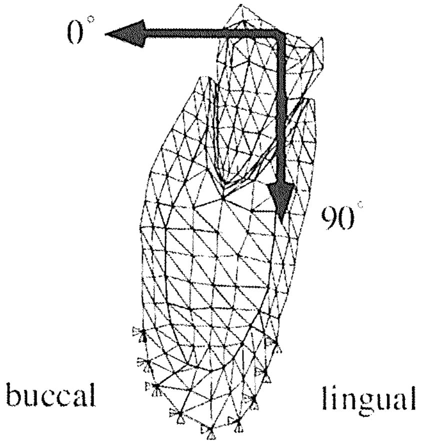

Fig. 2. Example of loading. Two axes indicate externally oriented horizontal loading (0 °) and inferiorly oriented vertical loading (90°), respectively.

Table 1. Material constants applied for the finite element models in this study.

Material	Young's modulus (M Pa)	Poisson's Ratio
Cortical bone	10000.0	0.20
Cancellous bone	30.0	0.32
Enamel	50000.0	0.30
Dentin	12000.0	0.30
Periodontium	1000.0	0.49
Pulp	1.0	0.49

modified from Stanford et al. (1960) and JSME (1988)

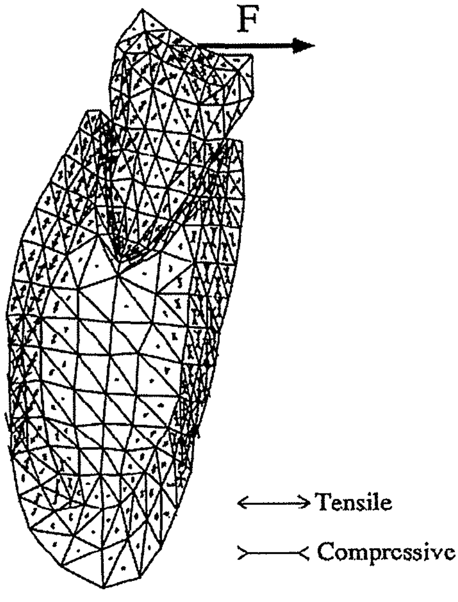

Fig. 3. Example of principal stress distributions. The chimpanzee model is loaded by lingually oriented horizontal stress (180°) (F). The first and second principal stresses are shown by two axes with a right angle in each element. In most elements, either the first or the second principal stress is close to zero, indicating that either tension or compression is dominant in each element.

Results

Figure 3 is an example of the mathematical experiments in which the chimpanzee models are loaded by an internally oriented force (180°). The principal stress distributions are shown (Fig. 3). High magnitude of stresses is observed in the cortical bone, enamel, and periodontium while they are low in magnitude in the cancellous bone and dentin. This is a general tendency regardless of the model and loading mode investigated.

The results are given by species in the following sections. I describe changes of principal stress distributions in relation to the loading orientation. I especially emphasize changes of the stress distributions near the tooth axis.

1. Chimpanzee

The tooth axis angle of the examined chimpanzee subject was 69.9 degree being measured from the external direction counterclockwise. This value was measured from the original CT image. The principal components of stress were analyzed under different loading angles (bite force direction). At loading angles lower than the tooth axis (hence supero-lingual to infero-buccally directed), compression is dominant on the buccal side while tension is dominant on the lingual side. At loading angles higher than the tooth axis (supero-buccal to infero-lingually directed), the reverse relationship is observed. At loading angles near the tooth axis, compression is almost even on the buccal and lingual sides. The average of the principal stress differences of all elements becomes minimum (54.7-59.4MPa) at the loading angle close to the tooth axis (70-80°) (Fig. 4). The average of strain energy of all elements also takes the minimum value (0.384-0.539 MPa) at the loading angle close to the tooth axis (70-80°) (Fig. 5).

2. Gorilla

The tooth axis of the examined gorilla subject was 92.3° (for the definition, see above). As is in the chimpanzee, at loading angles lower than the tooth axis, compression is dominant on the buccal side and tension is dominant on the lingual side. Likewise, at loading angles higher than the tooth axis, the reverse relationship is observed. Compression is nearly even on the buccal and lingual sides and at loading angles near the tooth axis. The average of strain energy of all elements also takes the minimum value (0.178-0.218 MPa) at the loading angle close to the tooth axis (80-90°) (Fig. 7). Like results from the chimpanzee, the minimum values of the principal stress differences (Fig. 6) and strain energy of all elements are observed under the loading along the tooth axis.

3. Human

The tooth axis of the examined human subject was 68.1°. The principal components of stress changes with loading angles (bite force direction) were similar to those of the chimpanzee and gorilla. At loading angles lower than the tooth axis, compression is dominant on the buccal side and tension is dominant on the lingual side. To contrast, at loading angles higher than the tooth axis, the reverse relationship is observed. Compression is nearly even on the buccal and lingual sides and at loading angles near the tooth axis. The average of the principal stress differences of all elements is minimized (57.6-58.3 MPa) at the loading angle close to the tooth axis (60-70°) (Fig. 8). The average of strain energy of all elements as well takes the minimum value (0.281-0.282 MPa) at the loading angle close to the tooth axis (60-70°) (Fig. 9). This result is concordant with those in mathematical experiments in the chimpanzee and gorilla.

Discussion

In this study, a high magnitude of stress was always observed in the hard materials such as cortical bone and enamel. It is acknowledged that cortical bone mainly resists

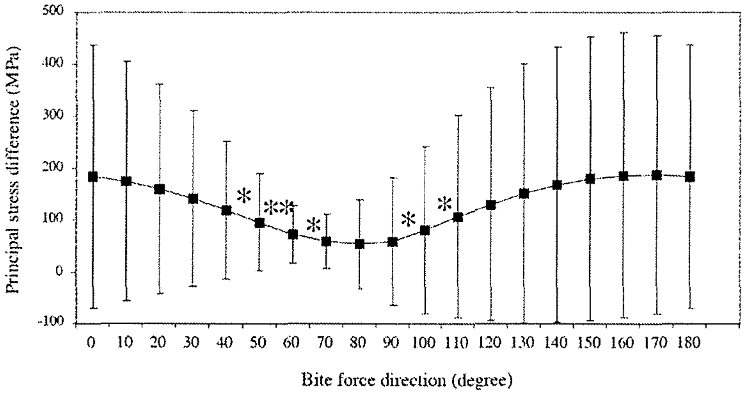

Fig.4. Average of principal stress differences of all elements in chimpanzee plotted against the loading angle. The 0° angle indicates externally oriented horizontal loading and the 180° angle indicates internally oriented horizontal loading. Asterisks indicate significant differences between neighboring plots (by t-test) (* $p<0.05$, ** $p<0.01$, *** $p<0.001$, **** $p<0.0001$).

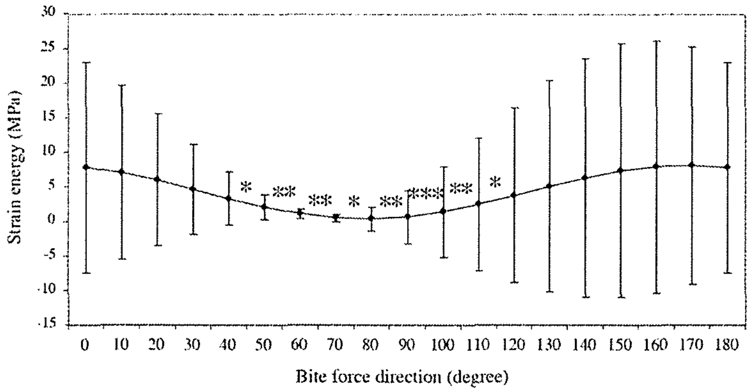

Fig. 5. Average of strain energy of all elements in chimpanzee plotted against the loading angle. For explanation of the figure, see Fig. 4.

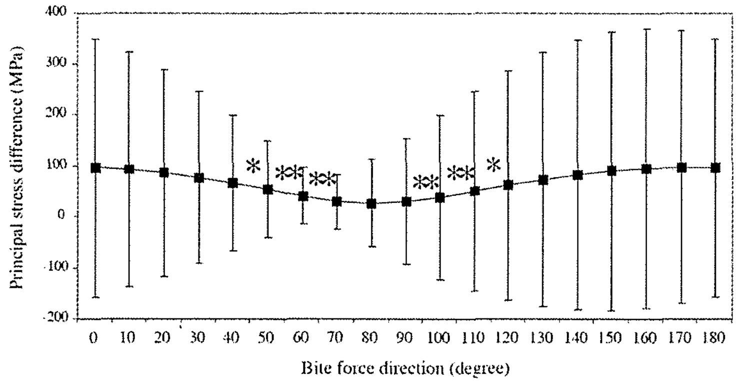

Fig. 6. Average of principal stress differences of all elements in gorilla plotted against the loading angle. For explanation of the figure, see Fig. 4.

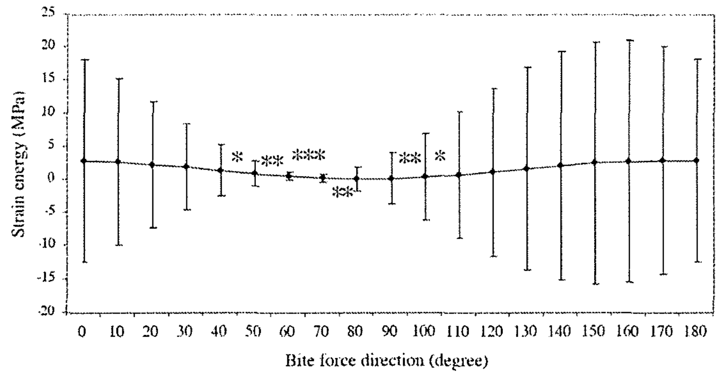

Fig. 7. Average of strain energy of all elements in gorilla plotted against the loading angle. For explanation of the figure, see Fig. 4.

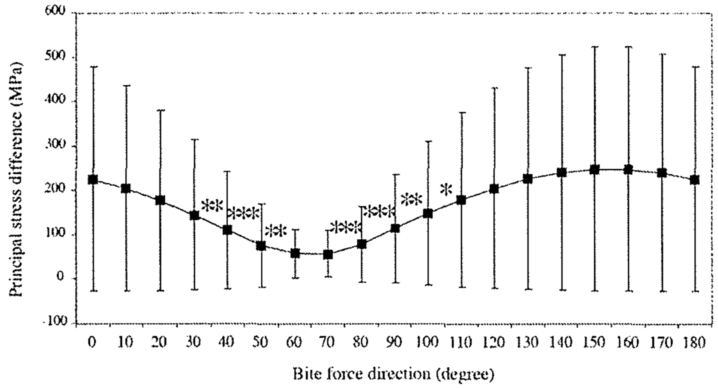

Fig. 8. Average of principal stress differences of all elements in human plotted against the loading angle. For explanation of the figure, see Fig.4.

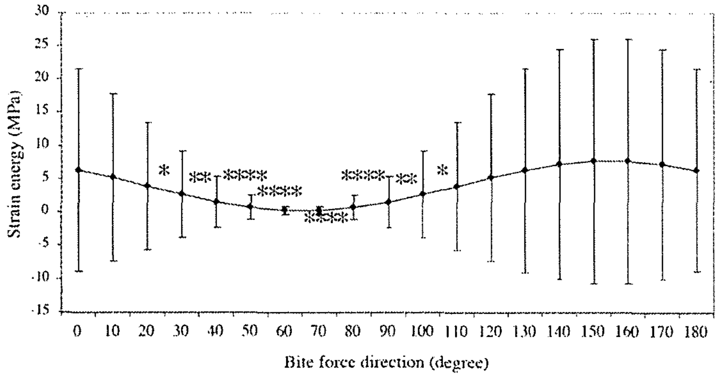

Fig. 9. Average of strain energy of all elements in human plotted against the loading angle. For explanation of the figure, see Fig. 4.

against external stresses while cancellous bone impacts (JSME 1988).

No significant difference of stress distributions appears at the mandibular corpus at molar level caused by bite force among the chimpanzee, gorilla, and human. This result means that stress distribution caused by bite force is largely influenced by the loading orientation relative to the tooth axis but not on the cross-sectional morphology of the mandibular corpus itself. The structural strength and stiffness become highest when the bite force orientation coincides with the tooth axis. Most likely, torsion and bending in the cross section are suppressed to the minimum under this condition because both sides of the corpus are loaded evenly. Bite force is loaded more or less along the tooth axis in average in non-human primates. Thus, cross-section of the corpus should be designed with resistance to compressive stresses.

Since the present analysis is based on the two-dimensional model, the lower level of the corpus is constrained. Due to this methodological restriction, torsion caused by horizontally directed bite force was not taken into account. Many studies have shown that torsion caused by bite force and muscular contractile forces potentially influences mandibular corpus morphology (Demes *et al.* 1986; Daegling *et al.* 1992; Ravosa 1996). For example, Hylander (1985) explained that the thick cross-sectional shape of the mandibular copse in robust australopithecines from torsional stresses resulted from food grinding. To test these arguments, three-dimensional FEM models should be developed where the stress distributions of the whole mandibular shape can be analyzed.

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